

Boeing Insulation-Installation Group (BIG)

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It is more prevalent than ever for commercial aircraft to use tubing with tight-fitting insulation to carry hydraulic fluid, compressed air, and fuel. Designed with stable and lightweight construction for manual handling, our team has prototyped novel tooling for installing insulation onto complex aerospace tubing. Our design reduces ergonomic risk to operators, reduces processing time, and improves production capacity.

Table of Contents

Executive Summary	3
Background	4
Problem Definition	4
Project Plan	4
Concepts Considered	5
System Integration	8
Design Evaluation	8
Summary & Recommendation	10
Appendices	11

Executive Summary

The Boeing Insulation-Installation Group (BIG) has been tasked with the challenge of finding a new method of installing insulation on titanium tubing used in a number of applications on Boeing aircraft. Currently, Boeing's Tube, Duct, and Reservoir Center (TDRC) installs the insulation on the tubing manually. This is a time-consuming and labor-intensive processes. It also presents a number of ergonomic issues for the installer. BIG, a team comprised of four senior mechanical engineering students at the University of Idaho, is using skills and knowledge gained during their undergraduate engineering curriculum to develop solutions to this challenging problem.

The BIG team first met with TDRC engineers and assessed the current installation method in order to clearly define the problem. BIG then brainstormed ideas, tested concepts, analyzed data, developed prototypes, and narrowed down the design path. This process led to the development of two viable design concepts that TDRC can pursue to address this ongoing manufacturing issue.

The two design concepts were (1) a powered device that pushes foam insulation over the titanium tubing; and (2) a powered tug that pulls the insulation over the tubing. These two concepts literally approached the problem from two directions. Each required design and fabrication of various components to produce a final assembly that was prototyped and tested.

Both innovative concepts are potential solutions to TDRC's tubing insulation issue, and either could be perfected and incorporated into Boeing's manufacturing process. However, based on BIG's testing and evaluation of the two concepts, we recommend that the "Foam Pusher" be given greater consideration by TDRC because the Foam Pusher has the highest potential for a complete, low-cost, and reliable solution to the problem.

Background

Boeing Company's TDRC facility in Auburn, WA assembles, tests and prepares all tubing, ducting and reservoirs for The Boeing Company's commercial aircraft. One of the project design criteria included applying closed-cell insulation on to a pre-formed titanium tube. It is common for tubes to be bent into various geometries and configurations. The current installation procedure requires an operator to manually force insulation over the bent tubing without any sort of mechanical assistance. This can be time-consuming and can create ergonomic risks. The manual process is taxing on the operator who may complete dozens of these insulated tube assemblies per day. In addition, manual installation can result in damage to the tube and insulation, resulting in waste and rework.

Problem Definition

The Boeing Insulation-Installation Group (BIG) is tasked with the objective of introducing novel tooling and manufacturing processes to insulate tubing components for The Boeing Company. Goals include improving the overall ergonomics and efficiency of the manufacturing process currently orchestrated by The Boeing Company's Tubing, Ducting and Reservoir Center (TDRC).

Project Plan

The plan for the project included the following basic steps:

- a. Introduction of the BIG team and the client and basic scoping of the project.
- b. Brainstorming session to develop a list of possible solutions.
- c. Site visit to Boeing TDRC facility in Auburn, WA, to observe and assess current process and to discuss the problem with TDRC engineers.
- d. Obtain samples of tubing and insulation materials for testing and evaluation.
- e. Conduct baseline testing of current process.

- f. Consult ergonomics experts on risks associated with current process.
- g. Purchase materials to begin testing and prototyping.
- h. Test and evaluate potential solutions and components.
- i. Rule out non-viable solutions and begin focusing on leading design concepts.
- j. Create engineering drawing package for prototype components and assemblies.
- k. Fabricate prototype components and assemblies.
- l. Conduct iterative testing and evaluation as the prototypes take shape.
- m. Conduct full-scale testing of final prototypes.
- n. Demonstrate the prototypes for the client at their TDRC facility.

Concepts Considered

Several concepts were considered during this project:

- a. **Air bearing** – The air bearing concept involved forcing compressed air between the tubing and the insulation to create a layer of air that would act as a bearing that would reduce the coefficient of friction between the tubing and the insulation. This concept was rejected because the air flow would cause the insulation to shift and create pathways for compressed air to escape around the tubing. A complete air bearing was therefore not achievable at the principal friction points between the tubing and the insulation.
- b. **Pipe puller** – The pipe puller concept involved the use of a flexible rod inserted through the insulation and tubing. The rod was then connected to the far end of the tubing and used to pull the tubing through the foam while the operator manually pushed the foam over the tubing. This procedure was only a partial solution and it still required the operation to apply a great deal of manual force to the tubing and insulation. The ergonomic risks of this concept were comparable to the current manufacturing process. However, this concept led to a better understanding of the dynamics



of the interaction between foam and tubing. This in turn helped inspire the Foam Pusher concept.

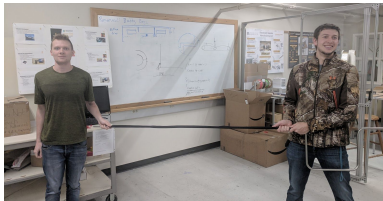
- c. **Finger trap** – The finger trap concept involved the use of a commercially available woven cable grip to grab to insulation and pull it over the tubing. This concept was expected to provide a method of pulling the foam insulation without causing damage. However, based on preliminary component testing, the BIG team determined that the cable grip squeezed and constricted the foam insulation around the tubing, causing greater normal force and, therefore, greater friction between the insulation and the tubing. The finger trap did, however, provide a reliable method of gripping the insulation from the forward end without damaging it.



- d. **Bull nose** – The bull nose concept was developed based on observations of the way that the foam moved around the bends of the tubing. We noted that the flat face of the ends of the foam insulation resisted bending around the inside radius of the tubing bends. This created a sticking point in the process. The bull nose was designed as a smooth rounded cap that helped guide the front end of the insulation around the tubing bends. While the bull nose concept was effective, it did not produce a significant improvement in the installation process.



- Fabric sleeve** – The fabric sleeve concept evolved from a desire to reduce the friction between the tubing and the foam insulation. The team tested the foam and the tubing to determine a baseline coefficient of friction. The team then tested the idea of inserting a fabric sleeve between the insulation and the tubing during installation and removing it when installation was complete. The sleeve successfully reduced the friction; however, it was difficult to retrieve and remove the sleeve from in between the tubing and the insulation after installation.



- e. **Tug** – The tug concept involved the design and fabrication of a powered device that would grip the tubing with rollers and travel along the length of the tubing. As the tug moved along the tubing, it would pull the foam over the tubing. The pulling device rolls along the tube while pulling the insulation behind it as it goes. The rollers use a set of springs to keep pressure between them and the tube. The rollers also have a rubber coating to increase friction and keep from damaging the tube. They are shaped to contour the tube as well as possible. The rollers are each driven by a high torque geared motor. The motor roller assembly slides into the

tube using a linear rail. This system keeps the assembly from binding when side loads are applied.

- f. **Foam Pusher** – The foam pusher concept was developed in response to our observations of how the foam reacted when it was pulled over the tubing. The team observed that as the foam was pulled, it stretched and necked down. This necking down constricted the foam around the tubing and increased the normal forces between the foam and the tubing. This in turn increased the friction force resisting the installation process. The team observed during evaluation of the pipe puller concept that by pushing the foam, it bunched up and



expanded somewhat in radius. This had the opposite effect of pulling the foam and resulted in a reduction of the normal forces. Also, by pushing the foam, it was much easier to control the speed of advance of the foam over the tubing. By keeping the foam insulation in continuous motion over the foam, the concept took advantage of reduced friction forces by converting static friction to dynamic friction. To develop this concept, the team had to overcome the challenge of pushing the foam, a very flexible and compliant material,

with sufficient force to drive it over the tubing. The team used a section of straight guide tubing to keep the foam straight and supported during the pushing process. A cup-shaped device was developed to uniformly apply pushing force to the back end of the foam section. The cup is pulled by a nylon strap and winch assembly guided by rollers to keep the pulling force aligned with the guide tube. Another challenge was developing a method of holding the tubing in place while the foam was pushed over it. The solution to this problem was to design a rubber “boat plug” or mandrel device that could grip the tubing from the inside with sufficient strength to oppose the force of the foam. Also, this mandrel had to be attached to the end of the guide tube. The foam pusher has been able to quickly and smoothly push the foam insulation over the tubing in a continuous motion and navigate the most difficult four-bend tubing configuration.



System Integration

The pipe puller as described in part (b) of concepts considered is used in combination with both the tug (e) and the foam pusher (f). In the tug design the puller allows the operator to pull the tubing through the insulation from the back as the tug makes its way along the pipe at the front of the insulation. This is important because for a brief moment after the tug has rounded the corner of the tubing it is no longer pulling in the correct axis to move the foam along the tube. When the pipe puller is attached to the tube in the foam pusher design it allows the winch and cup to apply force to the insulation while keeping the tube stationary.

The tug also requires use of the bull nose (d) described in concepts considered . It's purpose is to attach a clamp to the insulation without constricting it and increasing friction. This clamp can then be connected to the tug device. This is what the tug uses to apply force to the insulation. It's important that this connection is strong because of the large forces being applied by the tug. Used on it's own this piece could be made of plastic but as it goes around corners it will encounter significant forces. This means for the final design this will need to be made of metal.



Design Evaluation

When creating a DFMEA we found that the greatest risks were related to the motors and potential pinch points. Because all of the motors being used are high torque it's important that they are not powered on unintentionally. This could lead to something or someone getting caught in rollers or the winch mechanism. If the motors do get caught on something or bind up the motor controller may burn up. It is also possible in this case for the gearboxes on the motors to strip. Any one of these things will render the devices completely unusable. While a way to stop this has not been implemented in any of our current designs we would recommend adding some kind of current limiting circuit to the motor controller. Doing this would largely take care of these problems.

Another potential failure point is where the devices apply force to the insulation. If there are any sharp contact points it could damage the insulation and the piece would need to be thrown out. To mitigate this the cup on the pushing device was made to have smooth edges and on the pulling device the insulation is attached at the end where it will be cut off anyway.

To test the designs a scale was used to verify that they would have enough pulling and pushing force. The time to install with the devices was also measured to make sure that they met the design requirements.

Because both designs will never be manufactured at any significant scale the materials they are made of will not have any real environmental impact. That being said both designs are made of recyclable materials. The pushing device is made mostly of plywood which means it's also made of a renewable resource. Our design also in no way increases wasted material over the previous method of installation.

Device shall be multipurpose and be compatible with various bends	Use spring system with tensioner to allow for adjustment/fine tuning to determine if compatible with various tubes	Motor Housing, Rollers	02/27/2019	Success	Fine tune spring rates
Device shall be compatible with tubes of various lengths	Use 8020 railing to adjust for each type of tubing geometry to determine if compatible with various tubes	Motor Housing	02/27/2019	Success	Use square 8020 for weight reduction
All components shall have 95% reliability	Conduct fatigue analysis/FEA on components to predict service life of tool, look at spec sheets for statistics on reliability if available	Full assembly	03/06/2019	Success	Final prototype omponents fabricated with robust materials for longevity
The system should be able to operate off a standard 120V wall outlet, or air.	Ensure system is compatible with wall outlet if necessary	Full assembly	03/06/2019	Success	No need for powered or air equipment as current design
This project will be designed to operate in a controlled, indoor, and air conditioned environment.	Ensure system is will pose no risk to operators in vacinity	Full assembly	03/06/2019	Success	Systems fit indoors
Device shall insulate a tube in under three minutes	Test prototype and determine if time to assemble is satisfactory. Test multiple times to get an average installation time	Full assembly	04/03/2019	Success	Installation times are well within this time
Device shall reduce input from user	Compare ergonomic effects and implications of using tool and without using tool	Full assembly, operator	03/20/2019	Success	Devices significantly reduce user fatigue
This device should be user driven, staying in the constraints of the current working area.	Ensure that tooling fits within defined allotted area	Full assembly	03/20/2019	Success	Devices fit in workspace

Projected cost for production units shall be < \$1500.	Ensure system costs less that requirement	Full assembly	04/03/2019	Success	Devices cost significantly less than defined limit
Cost of the first prototype shall not exceed \$500.	Ensure system costs less that requirement	Full assembly	03/06/2019	Success	Devices cost significantly less than defined limit
Device shall maintain a consistent and uniform appearance	Test tool multiple times, observe effects on tubing and insulation, search for degradation or damage	Tubes, Insulation	04/03/2019	Success	Tubes have little to no wear
Device shall appropriately set insulation within tolerances for end conditions	Measure ends of tubes for tolerance after each installation	Full assembly, tubing and insulation	04/03/2019	Success	Insulation installation controlled by user
Device shall be compatible with tube diameters ranging from 3/8th - 1 inch	Test various tubing diameters using spring system for adjustment	Motor housing, tubing	02/27/2019	Success	Fine tune spring rates
Device shall not permanently warp tubing	Use tool as designed, analyze tubing for degradation or damage	Full assembly, tubing, insulation	04/03/2019	Success	Insulation have little to no wear
Device shall not destroy insulation	Use tool as designed, analyze insulation for degradation or damage	Full assembly, tubing, insulation	04/03/2019	Success	Insulation does not get damaged after initial installation (over several dozen installations it begins to show signs of wear)
The mechanism should be able to handle 50-100 a day, easily keeping up with the 5000 items a year.	Conduct fatigue analysis/FEA on components to predict service life of tool	Full assembly	04/03/2019	Success	Systems offer robust operation

Ergonomics- Green Performance-Red Versatility-Orange Cost Effectiveness -Blue

Conclusions

At the start of this project we tested a highly recommended compressed air solution. Ideally, as many would assume, this would lower the friction factor and add to the pushing force on the insulation. It was quickly realized that this method was far less than adequate toward a solution, while the air was not near near strong enough to even noticeably change the restriction. There was another idea to use pressure changing tanks between the insulation and the pipe. This idea was debunk quite quickly as well; not only did was there insufficient funding to purchase pressure vessels, but there was also a thought that the suction would visa-versa increase the friction between the two due to the un-rigidness of the insulation. Our last failing attempt was while searching for an assistive material that could be placed between the pipe and the insulation. While we did find that having a low friction cloth material between the tube helped the install time, there was now was to pull the cloth out when finished.

The paths that we found to work successfully were the “Chug & Tug” method and in parallel the “Pusher” method. Overall, both systems indicate satisfactory proof-of-concepts. The lightweight tug allows for agility and ease of operation, pulling the the insulation as a truck would pull a trailer, around the bends in the pipe. However, the system does inherently require for minor assistance from the operator while further development would be required. The system is not entirely autonomous and some user intervention is required. The same is true for the foam pusher system. The quasi-static state system allows for a more ergonomic approach to installation, yet it still requires the operator to guide the insulation along the tube, especially at sharp bends. Considering the solution used before these systems were developed, either design would significantly improve the ergonomics that the operator experiences during installation. User fatigue is greatly reduced and installation times are also decreased by a reasonable margin.

Recommendations

Based on the results, our recommendation would be to use the two mechanisms together, allowing the tug to navigate the pipe while the pusher feeds the insulation toward the tug. We believe the best approach would be to have an additional wireless controller, running the speed of the tug's motors and the speed at which the pusher is being reeled in. This concept would give the user the capability to be at either end of the pipe inspecting the workings of the semi autonomous device.

The pushing device should also be setup on a table that allows it to be at a comfortable height for the operator. The winch of the device should be able to be operated with a controller that can remain near the operator. Both of these improvements will improve the overall ergonomics of the system.

Appendices

I. DFMEA

System Tug
 Subsystem _____
 Component _____
 Design Lead _____
 Core Team _____

Potential Failure Mode and Effects Analysis (Design FMEA)

Key Date _____

FMEA Number 1
 Prepared By Michael Odell
 FMEA Date 1/28/2019
 Revision Date _____
 Page _____ of _____

Component	Item / Function	Potential Failure Mode(s)	Potential Effect(s) of Failure	S e v	Potential Cause(s)/ Mechanism(s) of Failure	P r o b	Current Design Controls	D e t	R P N	Recommended Action(s)	Responsibility & Target Completion Date	Action Results			
												Actions Taken	New Sev	New Occ	New Det
Rollers	Transfer motion from motors to pipe to move tug along pipe	Loss of friction on pipe (slip)	Uneffective driving force	4	Using a roller material with too low friction coefficient	4	Rollers slipping	2	32	Use a material with a high coefficient of friction.					0
Rollers	Transfer motion from motors to pipe to move tug along pipe	Crack due to compression	Unusable system	6	Using a material with poor fatigue properties or exceeding loading	2	None	2	24	Conduct FEA analysis using selected material characteristics if available.					
Shaft	Connects motor to roller	Failure due to torsion	Failure of power transmission	7	Using a material with poor fatigue properties or exceeding loading	3	Motor shaft disengaged	5	105	Conduct FEA analysis using selected material characteristics if available.					
Motors	Provide motion to rollers	Loss of control	Unintended power being supplied, pinch points	9	Poor electronic control, failure of safety systems	2	Unwanted motion from motors	8	144	Use a two-point operating system (roggle switch and floor pedal to initiate power to motors).					0
Motors	Provide motion to rollers	Burn out (servo)	Unusable system	6	Overloading servo	6	Motors smoking	4	144	Built in safety system to ensure supplied power does not exceed motor ratings.					
Motors	Provide motion to rollers	Does not provide enough torque	Unusable system	4	Using a weak motor	3	Tug not moving	2	24	Ensure motors are capable of providing desired torque.					
Tug Frame	Keep tug components together	Fracture due to fatigue	System will come apart	6	Using too thin of materials	2	Elastic bending of frame components	2	24	Run FEA simulation and understand fatigue characteristics. Beef up thickness where needed.					0
Finger Trap	Hold insulation	Loss of friction on insulation (slip)	Unusable system	4	Not enough grip from finger trap (cross sectional area).	3	Finger trap slipping	2	24	Augment finger trap with additional mechanisms to increase grip.					
Finger Trap	Hold insulation	Bind up at bends	Unable to insulate tube	3	Too much friction at certain points along tube.	8	Finger trap binds up at bends	3	72	Mechanism to relieve pressure.					
Finger Trap	Hold insulation	Pinches/tears insulation	Damage to insulation	6	Too much friction at certain points along tube.	4	Finger trap pinching/tearing insulation	3	72	Mechanism to relieve pressure					
Finger Trap	Connect insulation to tug	Breaks due to tension	Damage to insulation	7	Too much friction at certain points along tube.	1	Finger trap material stretching	1	7	Mechanism to relieve pressure					
Springs	Maintain contact between rollers and pipe	Failure due to fatigue	Improper force applied to rollers, insufficient power delivery.	3	Over-extension of springs, inappropriate max loading.	1	Spring does not return to normal shape	1	3	Select springs with appropriate spring constants.					0

System Pusher
 Subsystem _____
 Component _____
 Design Lead Michael Odell
 Core Team Boeing Insulation Installation Group (BIG)

**Potential
 Failure Mode and Effects Anal
 (Design FMEA)**

Key Date _____

Component	Item / Function	Potential Failure Mode(s)	Potential Effect(s) of Failure	S e v	Potential Cause(s)/ Mechanism(s) of Failure	P r o b	Current Design Controls	D e t	R P N
Boat Plug	Easily and securely attach guide pipe and titanium tubing	Plastic connection to guide pipe breaks	Loss of connection between guide pipe and titanium pipe	6	Excessive forces	7	Only for small scale	6	252
Boat Plug	Easily and securely attach guide pipe and titanium tubing	Copper pipe tabs bend and release boat plug	Loss of connection between guide pipe and titanium pipe	6	Excessive forces	7	Only for small scale	6	252
Roller	Stablize and hold guide pipe, foam, and strap	Operators hand gets caught between roller and strap	Major injury to operator	10	Operator tries to keep guide pipe or strap on roller	4	None	4	160
Cup	Push foam from rear by being pulled by winch	Cup gets caught on boat plug	Unable to perform process and/or damage to device	5	Inconsistent surfases to get caught on	8	Training and awareness	4	160
Boat Plug	Easily and securely attach guide pipe and titanium tubing	Rubber disconnects from titanium pipe	Loss of connection between guide pipe and titanium pipe	3	Excessive forces	7	Only for small scale	6	126
Mounting Tower	Keep Guide pipe stationary and static	Mounting tower is pulled towards winch and roller	damage to device, injury to operator, and/or unable to perform	3	Excessive forces	6	Only for small scale	4	72
Roller	Stablize and hold guide pipe, foam, and strap	Guide pipe, foam, and/or strap wanders side to side off roller	Bent guide pipe, detached boat plug, or less affective at performing	6	Guide pipe is not lined up with roller and winch	6	Operator holds and guide pipe and foam on roller	2	72
Hand Power Drill	Provide power to winch	Over heated motor	Unable to perform process	2	Excessive forces	7	None	4	56
Strap	Attach cup and winch	Strap is tangled or twisted	Unable to perform process OR unable to perform process safely	10	Incorrectly setup	4	Training and awareness	1	40
Cup	Push foam from rear by being pulled by winch	Paracord connecting cup to strap gets caught or cuts into foam	Damage to foam and/or damage to device	4	Incorrectly setup and connected to winch	4	Training and awareness	2	32

II. Puller Device Schematic

